Group14 TECHNOLOGIES

Low Cost Manufacturing of Advanced Silicon-Based Anode Materials

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Project ID: BAT268

Overview

Timeline

- Start Date: January 2016
- End Date: September 2018
- Percent Complete: 100%

Budget

- Total Project Funding
  - DOE: $2.81M
  - G14: $1.23M
- Funding received in FY 2017
- Funding for FY 2018-19
  - No-cost extension

Barriers

- Cost: Anode materials that contribute towards the DOE target of $125/kWh
- Performance: Silicon based anodes to improve Li-ion energy density for vehicles
- Life: Maintain current cycle life of graphite anode Li-ion batteries

Partners

Relevance

- **Cost**: Current Li-ion battery cost structure will not enable widespread use of battery electric vehicles (BEV) or plug-in hybrid electric vehicles (PHEV)
  - Current technology trajectory will increase performance, but also increase cost

- **Performance**: BEV and PHEV range needs to be extended by increasing Wh/kg and Wh/L and maintaining power capability

- **Cycle Life**: Batteries with short life time i.e. 2-3 years can be tolerated in consumer electronics but not vehicles

- **Group14 targets**:
  - **Reduce cost** of current graphite based anodes
  - **Improve capacity** – increase EV range
  - **Maintain cycle life** of current batteries

Milestones

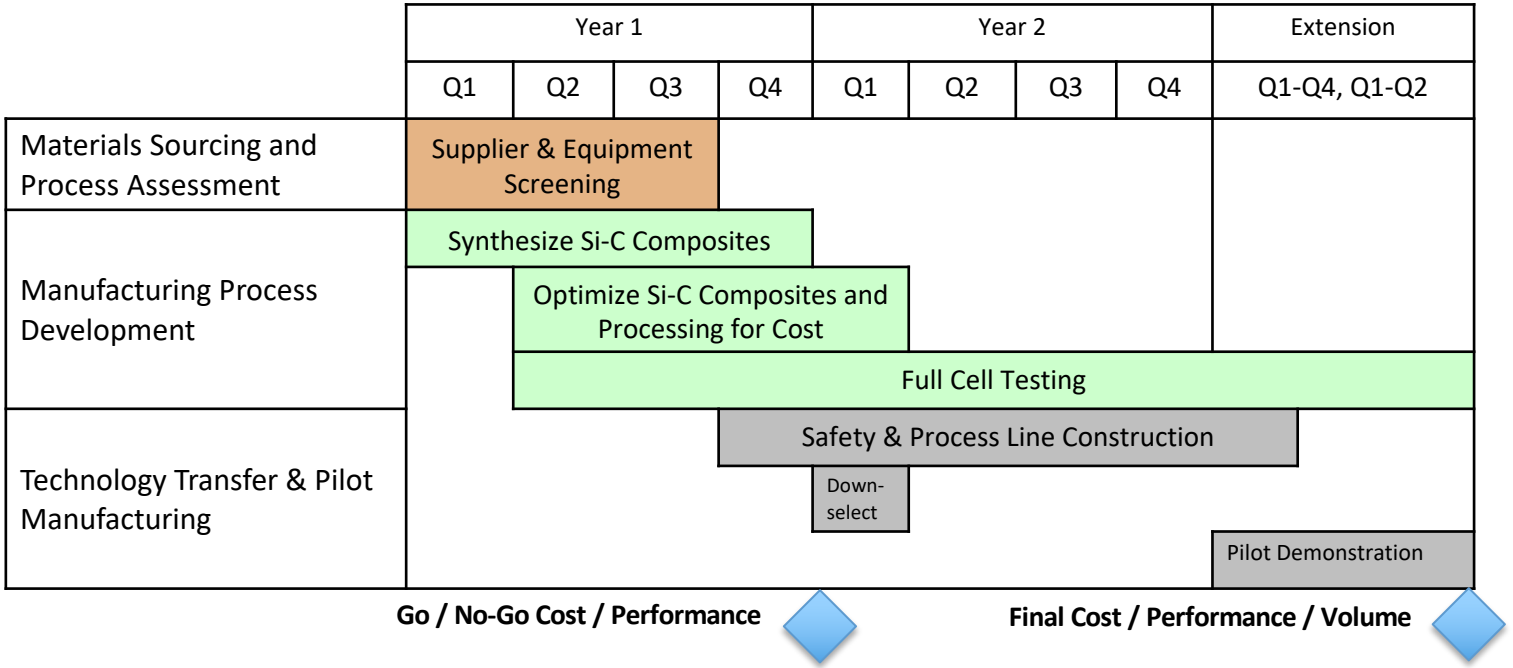
Year 1

Milestone	Type / Timing	Description
Supplier Identification	Technical / Q1	Identify minimum 2 suppliers for each new feedstock material required for Si-C composite. Materials must be available at full scale volume supporting < $125/kWh.
Sample Down-select	Technical / Q2	Down select to 3 lab-scale silicon samples for performance and cost
Synthesize Si-C	Technical / Q3	Synthesize 1x10g Si-C with 1000 mAh/g
Synthesize Si-C	Go/No-Go / Q4	Analysis indicates that the synthesized 1x1g Si-C with 1000 mAh/g is predicted to achieve 500 cycles at a projected cost of <$125/kWh

Year 2 / No-cost Extension Period

Milestone	Type	Description
Synthesize Si-C 1000 cycles	Technical / Q2	Synthesize 1x1g Si-C with 1000 mAh/g; predicted 1000 cycles; <$125/kWh projected cost
Performance Validation	Technical / Q3	Validate performance of at least one pilot-scale-synthesized material in the lab
Commission Equipment	Technical / No Cost Extension Period	Complete installation and commissioning of all new process equipment
Synthesis with Demo	Technical / No Cost Extension Period	The synthesis of 1 kg completes a demonstration 1000 mAh/g and predicted 1000 cycles at < $125/kWh at full scale volume

Approach / Strategy



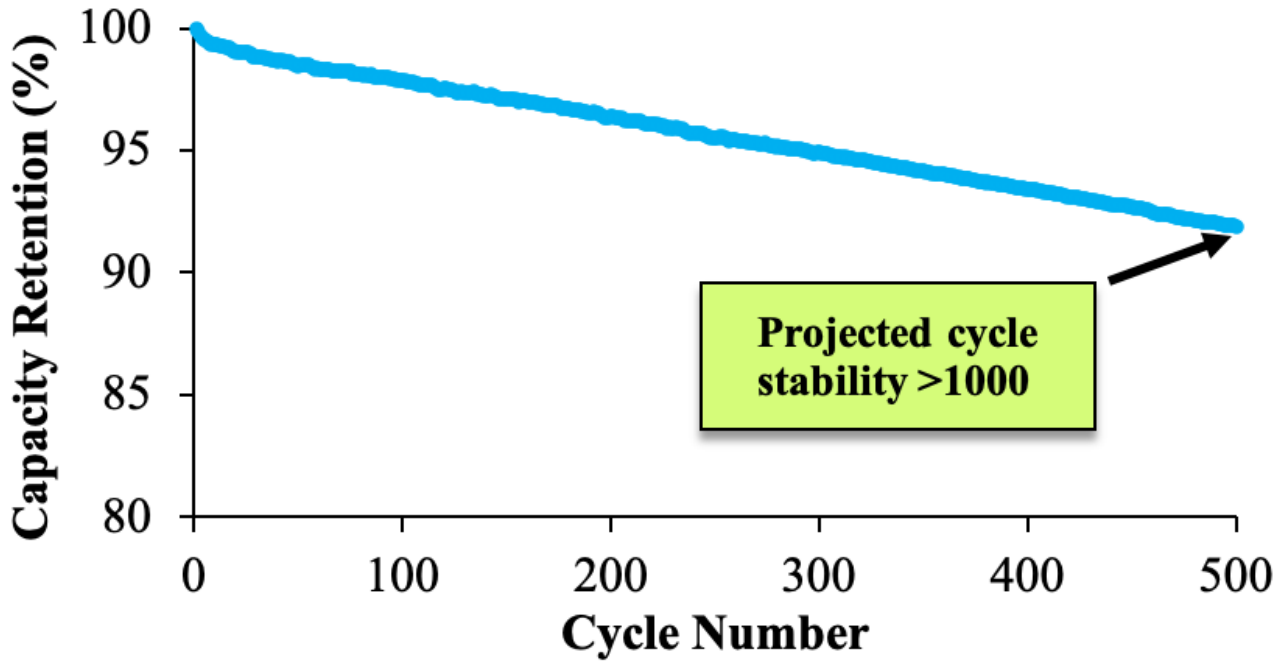
- Leverage EnerG2 carbon expertise in carbon to create an ideal silicon support matrix material
- Develop and implement low cost silicon synthesis process compatible with the carbon platform
- Demonstrate success of the approach in full cell LIBs
- Manufacture at pilot scale for qualification with LIB customers using low cost process

Technical Accomplishments:
3rd Party FCE Data for Pilot-Scale Si-C

Sample	Initial Charge Capacity (mAh/g)	Initial Discharge Capacity (mAh/g)	Initial Coulombic Efficiency (%)	Calculated Discharge Capacity [no dilution] (mAh/g)	Calculated Initial Coulombic Efficiency [no dilution] (mAh/g)
1	604	547	90.5	1918	88.7
2	604	556	92.0	2092	92.1

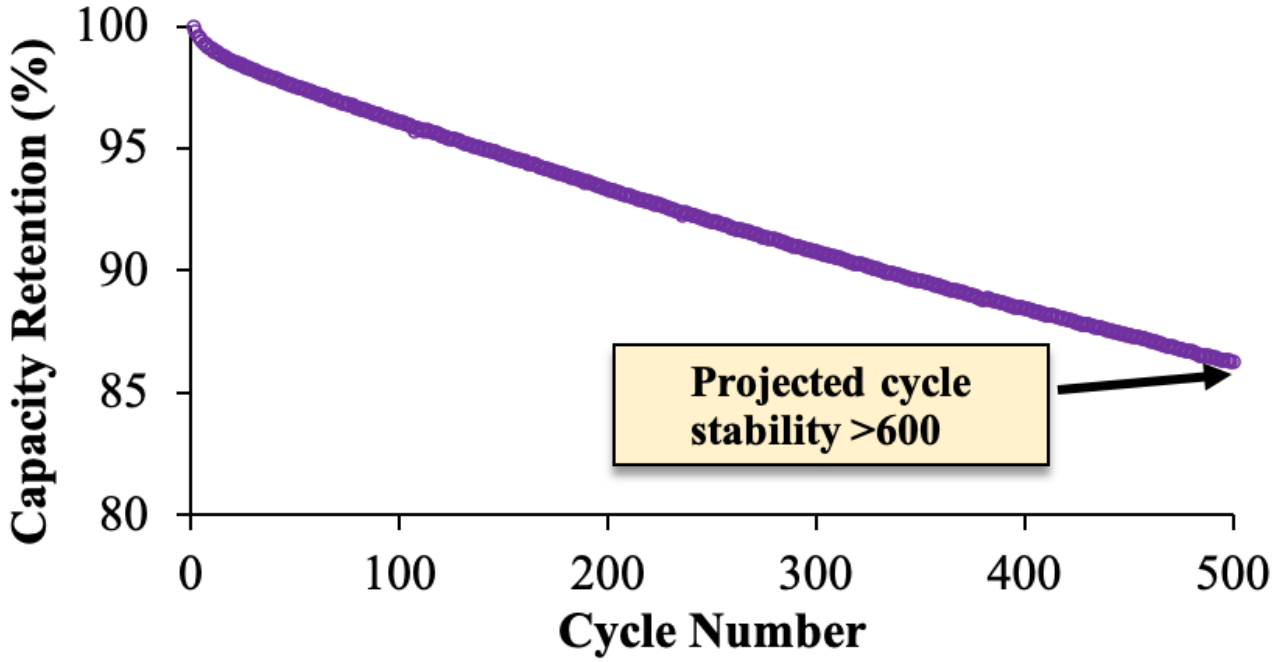
Data for half cell coin cells, anode ~12% Si-C diluted in graphite, counter electrode Li metal, discharge: 0.1 C CC-CV 5 mV 0.005 C cutoff, charge: 0.1 C CC 1.5V cutoff.

3rd Party Data for G14's Pilot-Scale Si-C: >1000 Cycle Stability at 25°C



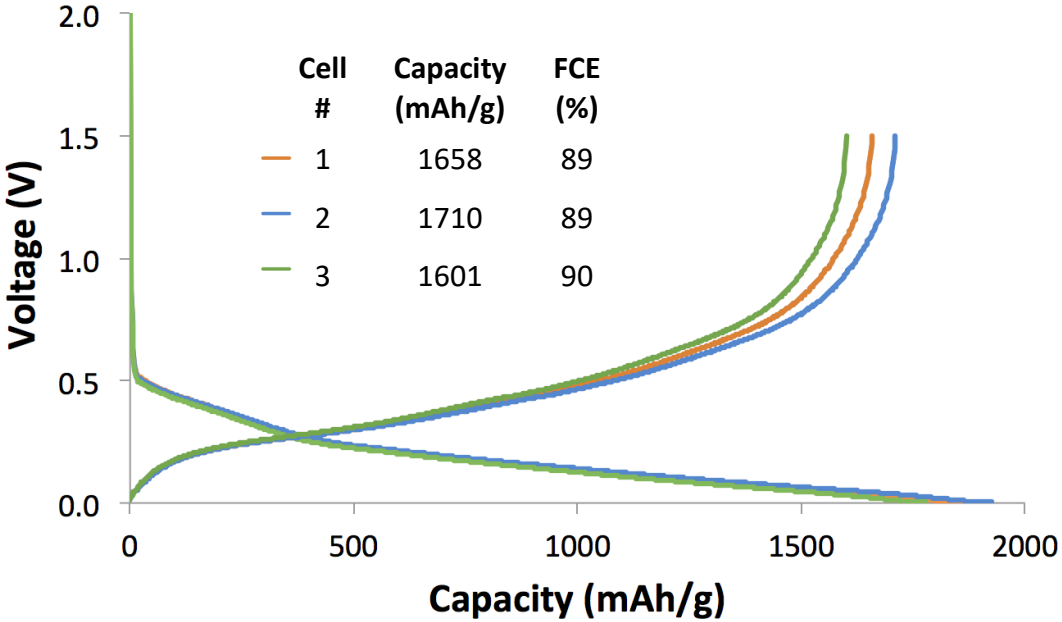
Average data for two full-cell pouch cells, anode ~12% Si-C diluted in graphite, NMC 622 cathode, cycled at 1C rate between 4.3V (CV charge 0.05C cut-off) and 3.0 V, electrolyte 1M $LiPF_6$ in EC:EMC:DEC = 3:5:2 v/v% + Additive.

3rd Party Data for G14's Pilot-Scale Si-C: >600 Cycle Stability at 45°C



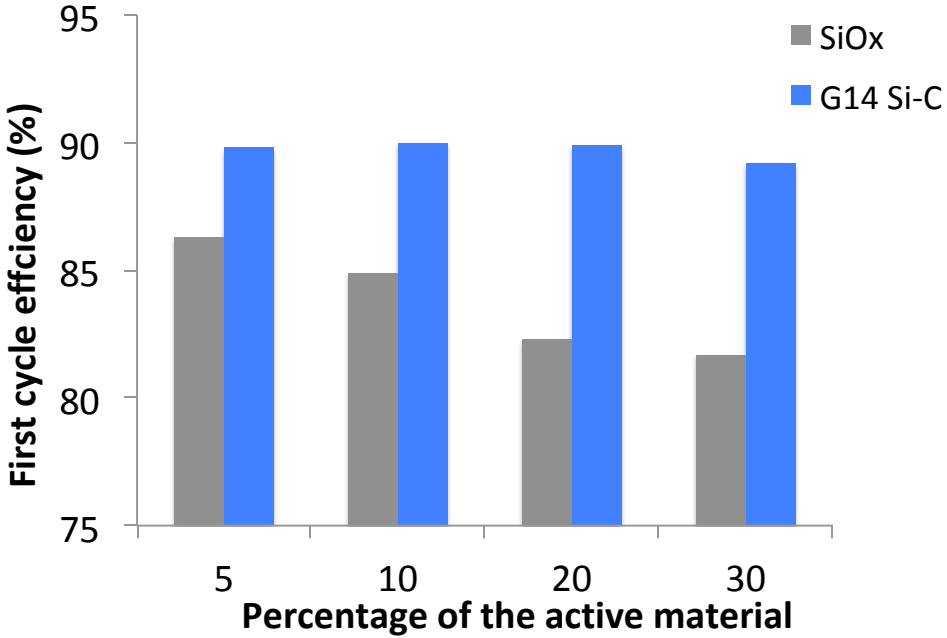
Average data for two full-cell pouch cells, anode ~12% Si-C diluted in graphite, NMC 622 cathode, cycled at 1C rate between 4.3V (CV charge 0.05C cut-off) and 3.0 V, electrolyte 1M $LiPF_6$ in EC:EMC:DEC = 3:5:2 v/v% + Additive.

3rd Party Data for G14's Pilot-Scale Si-C: Confirmation of High FCE



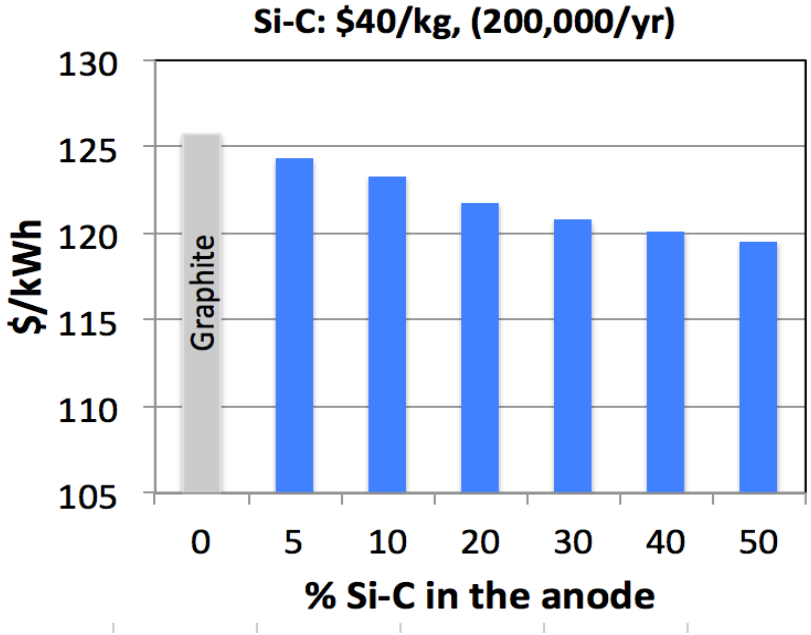
Swagelok half-cell, working electrode 90/5/5 AM/C/SBR-CMC, Counter electrode and reference: Li metal, electrolyte: 1M $LiPF_6$ in EC/DEC 3:7 with 10% FEC, formation: CC charge-discharge at C/25 between 5 mV and 1.5V.

Technical Accomplishments: Internal Confirmation of High FCE



Anode consists of 90% active (graphite +Si-C or SiOx), 5% CE, 5% binder. Cells tested in half-cell configuration with lithium metal counter electrode, 1M LiPF6 in EC:DEC (2:1 w/w)+10%FEC, cycled at C/10 rate between 1.5V and 5mV (CV cut-off at 5mV to C/20).

BatPaC Cost Modeling Consistent with Achieving Project Goal of <$125/kWh



Si-C = $40/kg, Graphite =$12.50		
Si-C % in anode	Battery systems /yr	
	100k	200k
0	133 $/kWh	126 $/kWh
20	129 $/kWh	122 $/kWh
30	128 $/kWh	121 $/kWh

Cost model using default values provided in the BatPaC 2018 model (v.3): 88 kWh battery pack for 300 mi range vehicle, Si-C cost of $40/kg and number of battery systems manufactured per year: 200,000.

Collaboration and Coordination with Other Institutions

- University of Washington Subcontract
- Pauzauskie Lab: Funded graduate student Matt Lim
  - Material modeling
  - Advanced characterization

- PNNL Subcontract
- Chongmin Wang Group: Funded post-doc
  - *In situ* TEM of Silicon Expansion
  - SAED
  - Advanced spectroscopy

Ready For Market

- Group14 Si-C material allows for cost parity of electric vehicles to ICE vehicles
  - Enables volumetric energy density improvement of greater than 35% over conventional graphite anodes
  - Potentially half the cost of graphite on a $/Ah basis

- Drop-in ready for blending with graphite, and can be easily integrated into current commercial anode and battery manufacturing lines

- Material performance from the pilot-scale manufacturing facility has been validated by multiple third parties

- Currently scaling up manufacturing capability to deliver 5t/month with funding secured from strategic investors including ATL, BASF, Cabot, and Showa Denko

Summary

- Group14 has developed a highly stable, low cost Si-C anode material
- Electrochemical performance of material produced at pilot scale completes a demonstration 1000 mAh/g and predicted 1000 cycles
  - In-house: >600 cycles, >1000 cycles with pre-lithiation
  - Third party: >1000 cycles @ 25ºC, >600cycles @45ºC
- BatPaC modeling using G14 Si-C is consistent with achieving less than $125/kWh at full scale production volume
- Due to DOE support, Group14 significantly increased production throughput, enabling industry validation and strategic partnerships
  - Validated material performance as well as scalability of the material production process
  - Secured funding from strategic investors for scaling manufacture to 5t/month